

# A new diagram of Earth's global energy budget

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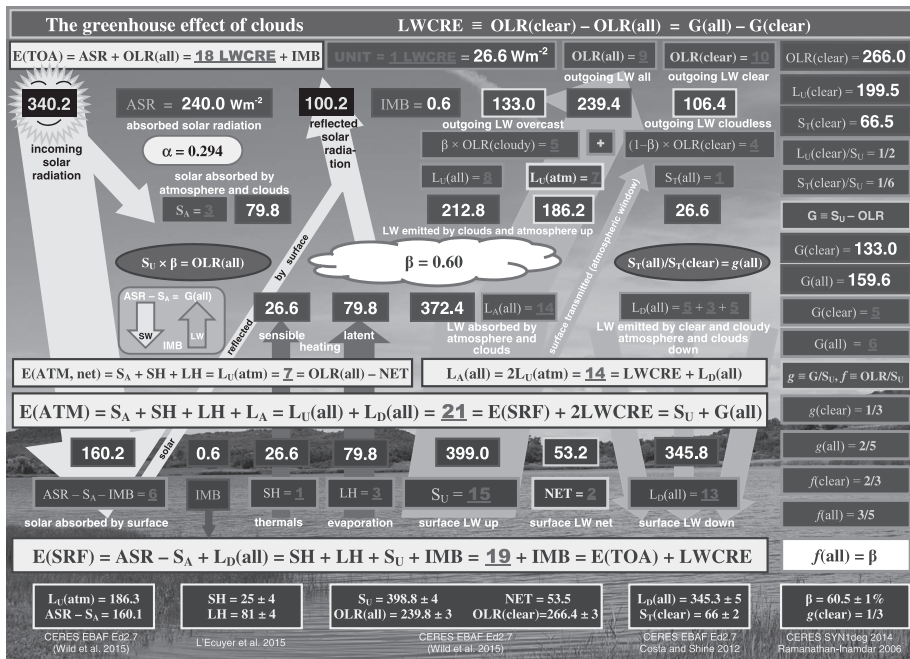
**Abstract** A new global mean energy budget diagram is offered for discussion and further examination. The main motivation for creating this figure was the observation that a quasi-discrete flux quantity structure seems to appear behind the best published energy budget data. This structure underneath the observed global energy flow system might represent an idealized, hypothetic normal (steady) state onto which the actual climatic regimes and their changes can be projected. The unit of the all-sky structure is the value of the flux element called longwave cloud radiative effect (LWCRE), termed also the greenhouse effect of clouds; under prevailing average conditions, it turns out to be numerically equal to the all-sky surface transmitted irradiance,  $S_T(\text{all})$ . There is also a clear-sky structure, as reported in earlier studies, where the unit of measure is one  $S_T(\text{clear})$ . Three important features are independent of the discrete units: (a) the energies at the surface are equal to the total energy at top-of-atmosphere plus one LWCRE; (b) the energies in the atmosphere are equal to the energy at the surface plus two LWCRE; (c) the shortwave (SW) radiation absorbed by the surface is equal to the longwave (LW) energy in the all-sky greenhouse effect. The aim of our study is to present the system as it reveals itself in the data; theoretical explanation is out of our recent scope.

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## Graphical Abstract



**Keywords** Earth's energy budget · Cloud radiative effect · Greenhouse effect of clouds · Energy balance equations

## Abbreviations

ASR	Absorbed (=incoming minus reflected) solar radiation
$\beta$	Cloud area fraction
CERES	Clouds and the Earth's radiant energy system
EBAF	Energy balanced and filled
$f$	Transfer function, $f = OLR/S_U$ , also called planetary emissivity
$g$	Greenhouse function, $g = G/S_U = 1 - f$
$G$	Greenhouse effect, $G = S_U - OLR$
GEWEX	Global energy and water exchanges project
ISCCP	International satellite cloud climatology project
$L_A$	Longwave radiation absorbed in the atmosphere
$L_D$	Downward emitted atmospheric longwave radiation at the surface, also termed DLR or 'back-radiation'
$L_U$	Upward emitted atmospheric longwave radiation at TOA, also termed 'thermal cooling to space'
LH	Latent heat (evapotranspiration)
LWCRE	Longwave cloud radiative effect
NET	Surface net longwave radiative cooling, $NET = S_U - L_D(all)$
OLR	Outgoing longwave radiation
$S_A$	Shortwave radiation absorbed in the atmosphere

SH	Sensible heat (thermals, convection)
SRF	Surface
$S_T$	Surface transmitted irradiance
$S_U$	Surface upward longwave radiation
$T_A$	Longwave transmittance, $T_A = S_T/S_U$
TOA	Top of the atmosphere

## 1 Introduction

From the diagram of Kiehl and Trenberth (1997), reproduced in the third and fourth assessment reports of IPCC in 2001 and 2007, through its updates (Trenberth et al. 2009; Trenberth and Fasullo 2012) and alternatives (Stevens and Schwartz 2012; Stephens et al. 2012) to the most recently published energy balance estimates (Wild et al. 2013, 2015; NASA LaRC Energy Budget Poster 2014; L'Ecuyer et al. 2015; Stephens and L'Ecuyer 2015), there are two types of representations of the global energy budgets. The most informative descriptions give the detailed decomposition of OLR into its three different energy flow elements: emitted by atmosphere, atmospheric window, and cloud radiation; the latter quantity is longwave cloud radiative effect [LWCRE =  $OLR(\text{clear}) - OLR(\text{all})$ ], Coakley and Baldwin 1984; Ramanathan 1987; Stephens and Greenwald 1991], rather than the realistic cloud top radiation. A more simplified approach displays only some of the elements listed above: atmospheric window was quantified in Stevens and Schwartz (2012), atmospheric upward emission in L'Ecuyer et al. (2015) and in Stephens and L'Ecuyer (2015); but none of these elements was shown in the IPCC (2013) diagram.

In this study we try to create a complete picture with the most recent observed data. The burden of our approach is that our diagram might seem overcomplicated, but the advantage is that all information is available in one frame, which might help to quantify not only the primary elements in the global energy budget but the secondary (composite, derived) energy flow components such as ratios, internal proportions, clear-sky and all-sky values, and certain greenhouse effect relationships as well.

The novelty of our diagram is threefold. First, an internal structure is presented, where all the energy flow elements are located in a grid, occupying their position in a given, specific order. Second, we try to connect the values of some fluxes with the cloud area fraction, which is also displayed. Third, there are well-defined relationships among the top-of-atmosphere (TOA), internal atmospheric (ATM) and surface (SRF) energy budgets, being valid independently of the lattice. Our graphic presents the whole structure in six different ways: we give the flux quantities (i) by their best observed value with estimated error bounds and the relevant data source of that flux element; (ii) by their proposed steady state (equilibrium) value; (iii) by their position in the structure expressed in integer units (the all-sky unit of measure is one LWCRE); (iv) by the relevant energy balance equations, describing definite connections between the surface, atmospheric and TOA energy contents; (v) by their specific whole number ratios and proportions; (vi) and by decomposing the outgoing longwave radiation and back-radiation (downward atmospheric LW emission) into their energy flow elements.

The numerical value of LWCRE in the structure, under equilibrium conditions, is equal to  $S_T(\text{all})$ ; see Fig. 1 and Table 1. There is also a clear-sky structure, where the fluxes are displayed in units of one  $S_T(\text{clear})$ , see Table 2.

**Table 1** All-sky equilibrium structure with our proposed best values and balance equations

Quantity	Unit: 1 $S_T(\text{all})$	Value ( $\text{W m}^{-2}$ )
LWCRE	1	26.6
NET [= $S_U - L_D(\text{all})$ ]	2	53.2
$S_A(\text{all})$	3	79.8
SH + LH	4	106.4
G(clear)	5	133.0
G(all)	6	159.6
$L_U(\text{atm})$	7	186.2
$L_U(\text{all})$	8	212.8
OLR(all)	9	239.4
OLR(clear)	10	266.0
$L_D(\text{atm})$	12	319.2
$L_D(\text{all})$	13	345.8
$L_A(\text{all})$	14	372.4
$S_U$	15	399.0

Total energy at TOA:  $E(\text{TOA}) = \text{ASR} + \text{OLR}(\text{all})$

Net atmospheric energy balance equation:  $E(\text{ATM, NET}) = S_A(\text{all}) + \text{LH} + \text{SH} = L_U(\text{atm}) = \text{OLR}(\text{all}) - \text{NET}$

$G(\text{all}) = S_U - \text{OLR}(\text{all}) = L_D(\text{all}) - L_U(\text{atm})$

$G(\text{clear}) = S_U - \text{OLR}(\text{clear}) = L_D(\text{all}) - L_U(\text{all})$

Gross atmospheric energy balance equation:

$E(\text{ATM}) = S_A(\text{all}) + L_A(\text{all}) + \text{SH} + \text{LH} = L_D(\text{all}) + L_U(\text{all}) = \text{ASR} + \text{OLR}(\text{all}) + 3\text{LWCRE} = S_U + G(\text{all}) = \mathbf{21}$  units of  $S_T(\text{all})$

$E(\text{ATM}) = E(\text{TOA}) + G(\text{all})/2$

Surface balance equation:

$E(\text{SRF}) = \text{ASR} - S_A(\text{all}) + L_D(\text{all}) = \text{SH} + \text{LH} + S_U = \text{ASR} + \text{OLR}(\text{all}) + \text{LWCRE} = E(\text{TOA}) + \text{LWCRE} = \mathbf{19}$  units of  $S_T(\text{all})$

$S_U = E(\text{TOA}) - S_A(\text{all}) = 2L_U(\text{atm}) + \text{LWCRE} = 2L_U(\text{all}) - \text{LWCRE}$

## 2 Data and relationships used in this study

The primal dataset we use is CERES EBAF Ed2.7, as presented in Wild et al. (2015, esp. Table 3). Surface upward longwave radiation ( $S_U$ ) is  $398.8 \text{ W m}^{-2}$  there. For a 24-year (1984–2007) period the NASA LARC/GEWEX experiment (Stackhouse et al. 2011) has  $S_U = 396.4 \text{ W m}^{-2}$ . The latest IPCC assessment report (IPCC 2013) presents  $398 \text{ W m}^{-2}$  within the error bounds of [394, 400]; the data analysis of L'Ecuyer et al. (2015) and a second optimization of Stephens and L'Ecuyer (2015), after applying relevant energy balance constraints, propose  $S_U = \mathbf{399 \text{ W m}^{-2}}$  within  $\pm 5 \text{ W m}^{-2}$  error margins. In our diagram we accept this mean value. (Quantities in bold typeset are the proposed elements of the idealized steady state where we do not indicate error bounds for them.)

Incoming solar radiation is  $340.4 \text{ W m}^{-2}$  in CERES EBAF, the reflected solar radiation from the surface is about  $25 \text{ W m}^{-2}$  and  $75 \text{ W m}^{-2}$  from the atmosphere and clouds. Trenberth and Fasullo (2012) and L'Ecuyer et al. (2015) have SW reflection altogether  $102 \pm 2$ ; Stephens and L'Ecuyer (2015) give  $100 \pm 4 \text{ W m}^{-2}$ . Absorbed solar radiation in the system in our study is set to be  $\text{ASR} = \mathbf{240.0 \text{ W m}^{-2}}$ . The part of ASR being absorbed

**Table 2** Clear-sky equilibrium values and relationships

Quantity	Unit: 1 $S_T(\text{clear})$	Value ( $\text{W m}^{-2}$ )
$S_T(\text{clear})$	1	66.5
$G(\text{clear})$	2	133.0
$L_U(\text{clear})$	3	199.5
$OLR(\text{clear})$	4	266.0
$L_D(\text{clear})$	5	332.5
$S_U$	6	399.0

Source MM4 and M7

$$S_U = 3OLR(\text{clear})/2$$

$$S_U = 2L_U(\text{clear})$$

$$S_T(\text{clear}) = S_U/6$$

$$L_U(\text{clear})/L_D(\text{clear}) = 3/5$$

$$S_U - S_T(\text{clear}) = L_A(\text{clear}) = L_D(\text{clear})$$

$$G(\text{clear}) = OLR(\text{clear})/2$$

$$L_D(\text{clear}) - L_U(\text{clear}) = G(\text{clear})$$

$$L_D(\text{clear}) + L_U(\text{clear}) = 2OLR(\text{clear})$$

$$S_A(\text{clear}) + (SH + LH)(\text{clear}) = L_U(\text{clear})$$

$$S_A(\text{clear}) = S_T(\text{clear})$$

$$(SH + LH)(\text{clear}) = G(\text{clear})$$

in the atmosphere is  $S_A = 78.1 \text{ W m}^{-2}$  in CERES EBAF;  $79 \text{ W m}^{-2}$  (74, 91) in IPCC (2013); and  $80 \text{ W m}^{-2}$  within the same limits in the detailed land–ocean assessment of Wild et al. (2015). We accept the latter mean with a value of  $S_A = 79.8 \text{ W m}^{-2}$ . These together let the surface solar absorption  $ASR - S_A = 161 \text{ W m}^{-2}$  in Trenberth and Fasullo (2012) and  $160.1 \text{ W m}^{-2}$  in Wild et al. (2015); we have  $ASR - S_A = 160.2 \text{ W m}^{-2}$  in our model.

Outgoing longwave radiation under all-sky conditions in the CERES EBAF Ed2.7 is  $OLR(\text{all}) = 239.8 \text{ W m}^{-2}$ ; the NASA/GEWEX product has  $OLR(\text{all}) = 237.8 \text{ W m}^{-2}$  as a 24-year mean. In our diagram we calculate with the value of  $OLR(\text{all}) = 239.4 \text{ W m}^{-2}$ .

Trenberth et al. (2009) introduce an imbalance flux element at the surface for oceanic heat absorption with a value of  $0.9 \text{ W m}^{-2}$ . Wild et al. (2015) provide  $0.6 \pm 0.4 \text{ W m}^{-2}$  for this term; Stephens and L’Ecuyer (2015) propose  $0.45 \pm 0.4 \text{ W m}^{-2}$ . A recent study on Earth’s net radiative imbalance says that IMB was  $0.47 \pm 0.67 \text{ W m}^{-2}$  during 1985–2012 (Allan et al. 2014). Hence, for equilibrium purposes, we might have properly chosen the zero mean value. Accepting  $ASR = 240.0 \text{ W m}^{-2}$ , an SW source of TOA and surface imbalance of  $IMB = ASR - OLR(\text{all}) = 0.6 \text{ W m}^{-2}$  is introduced into our graphic.

The clear-sky OLR in the most recent CERES EBAF TOA Ed2.8 is  $265.6 \text{ W m}^{-2}$ ; the diagram of Stephens et al. (2012), consistent with the earlier versions, gives  $266.4 \pm 3.3 \text{ W m}^{-2}$ . In our structure it is presented as  $OLR(\text{clear}) = 266.0 \text{ W m}^{-2}$ . For the longwave cloud effect, Stevens and Schwartz (2012) accept  $26.5 \text{ W m}^{-2}$ ; the diagram of Stephens et al. (2012) shows  $26.6 \pm 5 \text{ W m}^{-2}$  for the surface and  $26.7 \pm 4 \text{ W m}^{-2}$  at TOA; we use here LWCRE directly from its definition, given to one decimal figure, and have  $LWCRE = OLR(\text{clear}) - OLR(\text{all}) = 26.6 \text{ W m}^{-2}$ .

The components of OLR(all) obtained at TOA over cloudy and cloudless areas are described by Coakley and Baldwin (1984, Eq. 1), Charlock and Ramanathan (1985, Eq. 8), Stephens and Greenwald (1991) and Stevens and Schwartz (2012, Eq. 6) as:

$$\text{OLR}(\text{all}) = \text{OLR}(\text{cloudy}) \times \beta + \text{OLR}(\text{clear}) \times (1 - \beta) \quad (1)$$

Here  $\beta$  denotes cloud area fraction, and OLR(cloudy) is the emitted longwave irradiance at TOA obtained over the cloudy scenes; hence, from the known quantities,  $\text{OLR}(\text{cloudy}) = [\text{OLR}(\text{all}) - \text{OLR}(\text{clear}) \times (1 - \beta)]/\beta$ .

Downward longwave radiation,  $L_D$  (called also DLR or back-radiation) in CERES EBAF is  $345.3 \text{ W m}^{-2}$ . The updated energy balance of Stephens et al. (2012) based on their earlier accurate assessments gives  $345.6 \pm 9 \text{ W m}^{-2}$ . With our  $S_U = 399 \text{ W m}^{-2}$  we accept  $L_D(\text{all}) = \mathbf{345.8 \text{ W m}^{-2}}$ ; leaving a net surface longwave radiation, defined as  $\text{NET} \equiv S_U - L_D(\text{all}) = \mathbf{53.2 \text{ W m}^{-2}}$  (the CERES EBAF value is  $398.8 - 345.3 = 53.5 \text{ W m}^{-2}$ ).

Latent heat (LH) release by evaporation from the surface is  $80 \text{ W m}^{-2}$  in Trenberth and Fasullo (2012); in an update to the IPCC (2013) report, Wild et al. (2015) and Stephens and L'Ecuyer (2015) propose  $\text{LH} = 82 \pm 7 \text{ W m}^{-2}$ ; global hydrological cycle evaluations by L'Ecuyer et al. (2015) have  $81 \pm 4 \text{ W m}^{-2}$ ; Bengtsson (2014) suggests  $\text{LH} = 80 \text{ W m}^{-2}$ . In our diagram we accept the latter mean with  $\text{LH} = \mathbf{79.8 \text{ W m}^{-2}}$ . Surface non-radiative cooling ( $\text{LH} + \text{SH}$ ), according to Stevens and Schwartz (2012) and the data assessment of L'Ecuyer et al. (2015), is  $106 \text{ W m}^{-2}$ ; ECHAM6 results in  $106.5 \text{ W m}^{-2}$  (Stevens et al. 2013); we use  $106.4 \text{ W m}^{-2}$ , hence surface sensible heat (SH) in our work is set to  $\text{SH} = \mathbf{26.6 \text{ W m}^{-2}}$ .

Surface transmitted irradiance ( $S_T$ ) was calculated by Costa and Shine (2012) by detailed radiative transfer computations on 3D climatologies for clear skies. They found the value of  $S_T(\text{clear}) = 66 \text{ W m}^{-2}$ . Using a cloud area fraction of  $\beta = 0.67$  for a time period of 1983–1994 from ISCCP (Rossow and Schiffer 1999), they propose  $S_T(\text{all}) = (1 - \beta) \times 66 = 22 \text{ W m}^{-2}$ . A value for clear-sky LW transmittance,  $T_A = S_T(\text{clear})/S_U$  was presented by Miskolczi (2007, hereafter M7) as  $T_A = 1/6$ , leading to  $S_T(\text{clear}) = 66 \text{ W m}^{-2}$  for  $S_U = 396 \text{ W m}^{-2}$ , or with  $S_U = 399 \text{ W m}^{-2}$  to  $S_T(\text{clear}) = \mathbf{66.5 \text{ W m}^{-2}}$ . In our assessment we utilize the latter quantity.

The cloud area fraction from the NASA CERES SYN1deg product over a period of time 2000–2007 is  $\beta = 0.615$ ; then it shows a decrease to an average of  $\beta = 0.605$  for the years 2008–2014. Using a rounded value of  $\beta = \mathbf{0.6}$ , we suppose an equilibrium  $S_T(\text{all}) = (1 - \beta) \times 66.5 = \mathbf{26.6 \text{ W m}^{-2}}$  in our paper. Therefore, all-sky longwave absorption in the atmosphere, defined as  $L_A(\text{all}) \equiv S_U - S_T(\text{all})$  is  $\mathbf{372.4 \text{ W m}^{-2}}$ . Trenberth and Fasullo (2012) have  $374 \text{ W m}^{-2}$  for this value. The clear-sky longwave atmospheric absorption is  $L_A(\text{clear}) \equiv S_U - S_T(\text{clear}) = \mathbf{332.5 \text{ W m}^{-2}}$ .

The cooling to space expression (Green 1967; Goody and Yung 1989) made possible to treat column infrared cooling rates separately from internal transfer processes. The corresponding global and spectral average balance equation, as given by Stephens et al. (1994, Eq. 9); Inamdar et al. (2004 see def. in their Table 1), or Allan (2006, Eq. 4) is as follows:

$$\text{LW Cooling} = S_U - \text{OLR} - L_D = \text{NET} - \text{OLR} \quad (2)$$

where NET, following Allan (2006, Eq. 1) is as defined above. Note that LW Cooling is negative here. Introducing longwave upward atmospheric emission as its opposite,  $L_U \equiv -\text{LW Cooling}$ , by simple re-arrangement, applying the greenhouse effect definition

of Raval and Ramanathan (1989), we have another expression for the greenhouse effect (M7, Eqs. 5, 6):

$$G \equiv S_U - \text{OLR} = L_D - L_U \quad (3)$$

A direct arithmetic consequence is

$$L_U = S_A + LH + SH \quad (4)$$

These equations are exactly satisfied in the diagrams of L'Ecuyer et al. (2015), Stephens and L'Ecuyer (2015), and by the global average and CERES EBAF values in Table 3 of Wild et al. (2015). For a numerical quantity of  $L_U$ , Allan (2006) suggests a global mean of  $L_U = 183.5 \pm 5 \text{ W m}^{-2}$  with  $S_U = 396 \text{ W m}^{-2}$ ; Trenberth and Fasullo (2012) have  $187 \text{ W m}^{-2}$ . The CERES EBAF product gives  $186.3 \text{ W m}^{-2}$  (Wild et al. 2015); we accept this latter value in our diagram as  $L_U(\text{atm}) = \mathbf{186.2 \text{ W m}^{-2}}$ ; see Fig. 1. Note that several values in our structure differ only with  $0.1 \text{ W m}^{-2}$  from the best observed value.

### 3 Results: the structure

#### 3.1 Greenhouse effect and greenhouse factors

The value of the all-sky and clear-sky greenhouse effect is  $G(\text{all}) = S_U - \text{OLR}(\text{all}) = 399 - 239.4 = \mathbf{159.6 \text{ W m}^{-2}}$  and  $G(\text{clear}) = 399 - 266 = \mathbf{133 \text{ W m}^{-2}}$ . Their difference is called the greenhouse effect of clouds:  $G(\text{all}) - G(\text{clear}) = \text{LWCRE}$  (Ramanathan et al. 1989). The normalized greenhouse factors, defined as  $g(\text{all}) \equiv G(\text{all})/S_U$  and  $g(\text{clear}) \equiv G(\text{clear})/S_U$  are  $g(\text{all}) = \mathbf{0.4}$  and  $g(\text{clear}) = \mathbf{1/3}$ . The corresponding transfer functions, called also planetary emissivity (Bengtsson 2012) are  $f(\text{all}) \equiv \text{OLR}(\text{all})/S_U = 1 - g(\text{all})$ , and  $f(\text{clear}) \equiv \text{OLR}(\text{clear})/S_U = 1 - g(\text{clear})$ . With the NASA/GEWEX data, the measured value of  $f(\text{all})$  is  $237.8/396.4 = 0.5999$ . With the equilibrium quantities:  $f(\text{all}) = \mathbf{0.6}$  and  $f(\text{clear}) = \mathbf{2/3}$ . The  $g(\text{clear}) = 1/3$  relationship was noted by Ramanathan and Inamdar (2006), and is equivalent to  $G(\text{clear}) = \text{OLR}(\text{clear})/2$  or  $S_U = 3\text{OLR}(\text{clear})/2$  or  $S_U = 3G(\text{clear})$ . These ratios in the given numerical form were first described by M7.

#### 3.2 $L_U(\text{clear})$

In the clear-sky subset, outgoing thermal radiation is a sum of two components:  $\text{OLR}(\text{clear}) = S_T(\text{clear}) + L_U(\text{clear})$ ; having  $\text{OLR}(\text{clear}) = 266 \text{ W m}^{-2}$  and  $S_T(\text{clear}) = 66.5 \text{ W m}^{-2}$ , this leads to  $L_U(\text{clear}) = \mathbf{199.5 \text{ W m}^{-2}}$ . This value is the half of  $S_U = 399 \text{ W m}^{-2}$ . The relationship  $S_U = 2 L_U(\text{clear})$  was first described by Miskolczi and Mlynczak (2004, hereafter MM4) as a result of their computations.

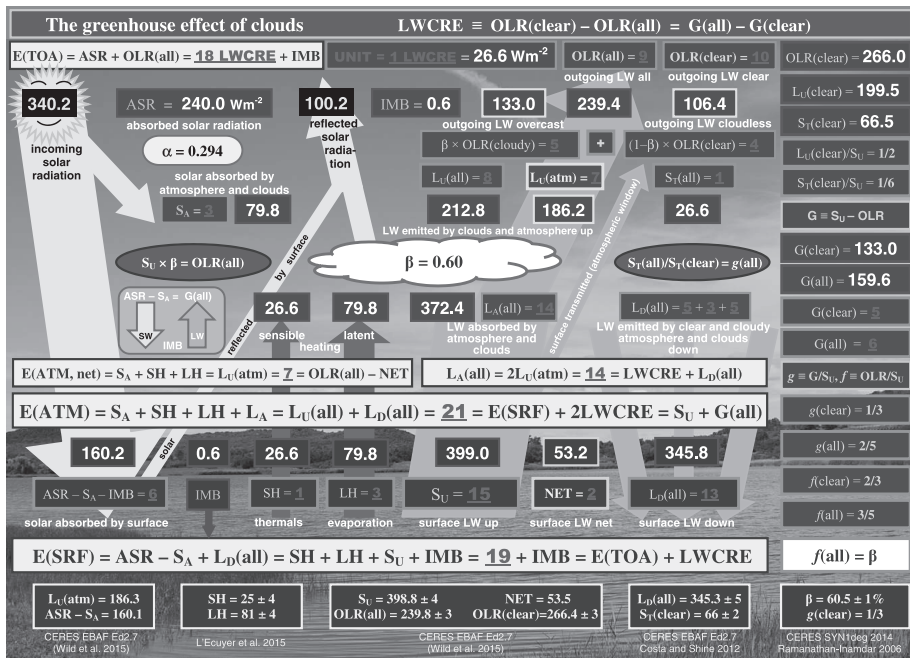
#### 3.3 $S_T(\text{all})$

Let us now realize that

$$S_T(\text{all}) = \text{LWCRE} \quad (5)$$

in the equilibrium set of quantities, both having a value of  $26.6 \text{ W m}^{-2}$ . This equality was first noticed by M7: “the LW effect of the cloud cover is equal to closing the IR





**Fig. 1** Global mean energy budget and the greenhouse effect of clouds. Discrete quantities are in units of one LWCRE; the quantity for  $\text{OLR}(\text{all}) = 239.8 \text{ W m}^{-2}$  of CERES EBAF v2.7 (see Wild et al. 2015) is  $\text{LWCRE} = 26.64 \text{ W m}^{-2}$ ; we display the structure to one decimal figure. The net atmospheric energy balance equation is from the cooling-to-space approximation;  $L_U(\text{atm}) = 7 \text{ units} = 186.2 \text{ W m}^{-2}$ .  $L_U(\text{all})$  is the total atmospheric and cloudy contribution to  $\text{OLR}(\text{all})$ . The outgoing radiation over cloudy areas is  $\text{OLR}(\text{cloudy})$ ; its contribution to  $\text{OLR}(\text{all})$  is  $\beta \times \text{OLR}(\text{cloudy})$ . The clear-sky contribution to  $\text{OLR}(\text{all})$  is  $(1 - \beta) \times \text{OLR}(\text{clear})$ . The values of  $L_U(\text{clear})$ ,  $S_T(\text{clear})$ ,  $f$ ,  $g$ , their relationships, and  $S_T(\text{all}) = \text{LWCRE}$  are from M7. Best observed and computed values with their estimated error margins and some data sources are also shown in the *bottom rows* of the diagram. Fluxes are in  $\text{W m}^{-2}$ ;  $g$ ,  $f$  and  $\beta$  are dimensionless

atmospheric window". A possible physical explanation is that the surface transmitted longwave energy being *lost* in the atmospheric window is *gained back* by the cloud greenhouse effect.

A direct consequence: the total ('up plus down') longwave cloud effect (LWCRE at TOA + LWCRE at the surface), equals to the surface net LW radiation:  $NET \equiv S_U - L_D(\text{all}) = 2 \text{ LWCRE}$  (see for example Stephens et al. 2012). This equality is numerically justified, and expressed in the fundamental relationship that the energies in the atmospheric budget equal to the energies at the surface plus the double of the greenhouse effect of clouds:

$$E(\text{ATM}) = E(\text{SRF}) + 2LWCRE \quad (6)$$

Notice that  $\text{LWCRE} = \text{OLR}(\text{clear})/10$  in the data, therefore, from  $G(\text{clear}) = \text{OLR}(\text{clear})/2$ , we have  $G(\text{clear}) = 5 \text{ LWCRE}$  and  $G(\text{all}) = 6 \text{ LWCRE}$ ; further,  $\beta \times \text{OLR}(\text{cloudy}) = G(\text{clear})$  in the matrix. Involving  $S_U$  from the definition of  $S_U = \text{OLR}(\text{all}) + G(\text{all}) = \text{OLR}(\text{clear}) + G(\text{clear})$ , we can immediately obtain  $S_U = 15 \text{ LWCRE}$ .

The system determines the necessary place of the remaining energy flow components as well: atmospheric solar absorption:  $S_A = 3$  LWCRE; the downwelling radiation at the



surface,  $ASR - S_A + L_D(\text{all}) - S_U$ , is balanced by the sensible and latent heat transfer,  $SH + LH = 106.4 \text{ W m}^{-2}$  (being equal to 4 LWCRE); from where  $SH = 1 \text{ LWCRE}$  and  $LH = 3 \text{ LWCRE}$  in the pattern, with the important relationships of  $SH + LH + LWCRE = G(\text{clear})$  and  $SH + LH + NET = G(\text{all})$ .

Now we have arrived at the following expression, showing the relationship between the equilibrium values of  $OLR(\text{all})$ , cloud cover fraction and  $S_U$  as  $OLR(\text{all}) = S_U \times \beta$ . It is straightforward from here that  $G(\text{all}) = S_U \times (1 - \beta) = ASR - S_A$  in the equilibrium pattern.

This point allows us to formally decompose  $L_D(\text{all})$  into the following three energy flow elements as

$$\begin{aligned} L_D(\text{all}) &= \beta \times OLR(\text{cloudy}) + \beta \times G(\text{clear}) + (1-\beta) \times L_D(\text{clear}) \\ &= G(\text{clear}) + \beta \times G(\text{clear}) + G(\text{clear}) = 13 \text{ LWCRE} \end{aligned} \quad (7)$$

Our final formula in the framework, under the steady-state conditions of  $\beta = 0.6$  and  $OLR(\text{all})/S_U = 3/5$ , connects planetary emissivity (all-sky transfer function) to the cloud cover fraction as

$$f(\text{all}) = \beta \quad (8)$$

Note that the value of  $\beta = 0.6$  in these relationships assumes that the cloud layer is completely opaque in the infrared. If not (as for example, in realistic cirrus clouds), a higher area fraction is possible. This might be an explanation why the observed CERES cloud area fraction is higher by about 0.5 % than the equilibrium requirement of  $\beta = 0.6$ .

The whole structure in units of one LWCRE =  $S_T(\text{all})$  is shown in Table 1. The clear-sky subset is valid independently, as shown in Table 2, in units of one  $S_T(\text{clear})$ ; source: M7. The cloudy decomposition depends on  $\beta = 0.6$ .

## 4 Discussion

The question may arise, is the Earth's radiation budget constrained? Our study suggests yes, there is a strict constraint, operating by the available absorbed energy, through the greenhouse effect of clouds. The 'how' is a theoretical problem, far beyond the scope of our present work where we simply describe the numbers and ratios as they reveal themselves in the data. But it must be noted that the unique *global* average state can be implemented through several regional and vertical temperature fields and precipitation distributions. Climatic regime fluctuations, and shifts, might happen through possible reorganisations of the cloud cover, cloud type and height, if atmospheric composition changes. Hemispheric and seasonal dislocation of insolation may well lead to global climate change, under one and the same global average greenhouse function value. Hence, our study says nothing about the equilibrium climate sensitivity; it only suggests that the equilibrium greenhouse sensitivity is zero.

Why does the system prefer a unique discrete state rather than using continuous flux variables? Internal symmetries might help to maintain the overall stability of the structure. For example, the equality

$$OLR(\text{all}) = S_U \times \beta \quad (9a)$$

means that the cloud-covered part of the surface radiates the amount of  $OLR(\text{all})$ , while the cloudless part of the surface emits the remaining  $G(\text{all})$ . Also,

$$\text{OLR}(\text{all}) = S_U - \beta \times \text{OLR}(\text{clear}) \quad (9b)$$

leads to  $\beta \times \text{OLR}(\text{clear}) = G(\text{all})$ , representing a cross-determination between the clear and the cloudy atmospheric portions. Further inter-dependence is shown in

$$\text{OLR}(\text{all}) = G(\text{clear}) + (1-\beta) \times \text{OLR}(\text{clear}) \quad (9c)$$

that is,  $\text{OLR}(\text{all})$  can be symmetrically decomposed to  $\text{OLR}(\text{all}) = G(\text{clear}) - \text{LWCRE} + G(\text{clear})$ .

This compilation

$$\text{OLR}(\text{all}) = G(\text{all}) + \beta \times G(\text{clear}) \quad (9d)$$

describes again a cross-determination, as

$$\text{OLR}(\text{all}) = \beta \times G(\text{clear}) + (1-\beta) \times S_U \quad (9e)$$

At the bottom of the atmosphere, the surface has two energy incomes, solar absorption and longwave back-radiation. Now it turns out that the shortwave energy absorbed by the surface covers entirely the energy of the all-sky greenhouse effect:

$$\text{ASR} - S_A = G(\text{all}) \quad (10)$$

The principal relationship is that the energy flows at the surface are equal to the total (incoming plus outgoing) energy flows at TOA plus the greenhouse effect of clouds:

$$E(\text{SRF}) = E(\text{TOA}) + \text{LWCRE} \quad (11)$$

The validity of Eq. (10) and (11) does not depend on the lattice structure but exhibits very general determinations.

Note that CERES EBAF Ed2.7 gives  $\text{OLR}(\text{all}) = 239.8 \text{ W m}^{-2}$  and  $S_U = 398.8 \text{ W m}^{-2}$  (Wild et al. 2015, Table 3), while the equilibrium surface radiation corresponding to this OLR would be  $S_U = 399.67 \text{ W m}^{-2}$ . If everything else remains unaltered, a further 0.16 K global surface warming is needed to reach the equilibrium.

The challenge ahead is to examine, what sort of physical principles, material conditions and dynamic processes are able to keep the observed ratios fixed under continuously changing atmospheric greenhouse gas concentrations.

## 5 Summary

A set of discrete parameters reveals itself in the data, far within to the uncertainties of observations, in some cases exactly at the best observed values, fitting into a particular ‘quantized’ pattern and satisfying specific whole number proportions and relationships. The clear-sky unit of measure is  $S_T(\text{clear}) = S_U/6 = 66.5 \text{ W m}^{-2}$ ; the corresponding relations were first presented in MM4 and M7. The all-sky unit is  $\text{LWCRE} = 26.6 \text{ W m}^{-2}$ . If the effective cloud area fraction is  $\beta = 0.6$  (and it is very close to it in the observations),  $\text{LWCRE}$  equals to  $S_T(\text{all})$ . The shortwave part, as well as the balance equations, fit into the structure on their own. The flux decomposition of  $\text{OLR}(\text{all})$  and  $L_D(\text{all})$  depend on the value of  $\beta$ . There are relationships that are not depending on the whole number structure: surface energy is equal to the total energy at TOA plus  $\text{LWCRE}$ , and the atmospheric energy content is equal to the surface energies plus  $2 \text{ LWCRE}$ ; further, the shortwave energy absorbed by the surface equals to the longwave energy content of the all-sky

greenhouse effect. These relationships indicate that the distribution of energy in the system is not a free variable of the atmospheric greenhouse gas composition but predetermined by the boundary conditions. Physical explanation and theoretical interpretation require further research.

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